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Natural light controls and guides in buildings. Energy saving for electrical lighting, reduction of cooling load

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ABSTRACT

The residential sector is responsible for approximately a quarter of energy consumption in Europe. This consumption, together with that of other buildings, mainly from the tertiary sector, makes up 40% of total energy consumption and 36% of CO_2 emissions. Artificial lighting makes up 14% of electrical consumption in the European Union and 19% worldwide. Through the use of well-designed natural lighting, controlled by technologies or systems which guarantee accessibility from all areas inside buildings, energy consumption for lighting and air conditioning can be kept to a minimum. The authors of this article carried out a state of the art on the technologies or control systems of natural light in buildings, concentrating on those control methods which not only protect the occupants from direct solar glare but also maximize natural light penetration in buildings based on the occupants' preferences, whilst allowing for a reduction in electrical consumption for lighting and cooling. All of the control and/or natural light guidance systems and/or strategies guarantee the penetration of daylight into the building, thus reducing the electrical energy consumption for lighting and cooling. At the same time they improve the thermal and visual comfort of the users of the buildings. However various studies have also brought to light certain disadvantages to these systems.

Contents

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1. Introduction

The residential and tertiary sector, makes up 40% of total energy consumption [1–8] and 36% of CO_2 emissions [9]. According to the International Energy Agency (IEA) [10], artificial lighting makes up 14% of electrical consumption in the European Union and 19% worldwide.

By acting on energy efficiency in buildings, it is possible to reduce energy consumption and therefore CO_2 emissions into the atmosphere [11,12]. Lancashir et al. [13] reported that each kWh of energy saved prevents the emission of 680.39 g of carbon dioxide, 5.67 g of sulfur dioxide, and 2.27 g of nitrogen oxide.

Many studies have been able to demonstrate the importance of natural light in buildings. Natural light significantly influences both the balance of energy use in buildings and actual human activity [14–17], offering the occupants comfort and health benefits, given that it plays an important biological role in the control of the physiological and psychological rhythms of living beings [18–20].

However, due its changing nature, it is necessary to control and guide natural light in order to supplement or replace artificial lighting. If it is not controlled, natural light can have a negative impact on the environment as excessive solar gains lead to an increase in energy consumption for cooling. On the other hand, most natural light control systems concentrate on minimizing the negative impact of natural light, whilst ignoring its positive impact. Through aiming to reduce the external heat load caused by solar radiation in a building, the amount of natural light often becomes insufficient and results in an increase in energy used for electrical lighting [21]. Thus, for example, windows allow daylight to enter into and illuminate the interior of a building, yet the effects of the natural light decrease as one moves away from the windows, making the use of artificial illumination a necessary complement [22].

Therefore, through a well-designed, controlled use of natural light, employing technologies or systems which ensure the penetration of light throughout the whole building, energy consumption designated to lighting and air conditioning can be kept at a minimum [23–35].

The authors of this article carried out a state of the art on the technologies or control systems of natural light in buildings. The efficiency of each of these systems in the reduction of energy consumption was evaluated. Specifically, the research concentrates on those control methods which not only protect the occupants from direct solar glare but also maximize daylight penetration into buildings based on the occupants' preferences, whilst allowing for a reduction in electrical consumption given over to lighting and cooling.

2. Impact of control systems of natural light

Electric lighting energy consumption [kWh] in conventional office buildings is as much as 35% of the total electric load – demands that are generated primarily during the day when daylight is abundant. Since the energy drawn for electric lighting is ultimately converted into heat, there is additionally a load on the cooling system. Proportional to the total energy used, electric lighting can add as much as 16% to the cooling energy bill, such that the combined electricity costs for lighting and cooling are almost 50% of total electric demand. While total energy consumption is made up of both electricity and fossil fuel energy uses, daylighting alone can reduce total energy use by as much as 25–30%, one of the most cost-effective investments for energy and carbon savings world-wide [21].

The economic impact of ignoring daylight is even more problematic because it is an electric load in buildings – for which source or primary energy costs are significant. 1 kW of power on site uses approximately 3–4 kW of primary energy, with the rest lost as heat up the chimney at the power plant. In conventional coal or oil fired power plants, only 35–40% of the primary energy is converted into power with a further 6% of the energy produced at the power plant lost in transmission. In developed economies such as the USA, Japan, Germany, power plants are to blame for approximately 50% of all CO_2 emissions. Over 40% of each nation's total energy consumption in developed economies is used for heating, cooling, air conditioning, lighting and other power requirements in buildings [21].

In addition, the benefits of a daylight building extend beyond simple energy savings [36,37]. Numerous studies also indicate that daylighting can help increase worker productivity and decrease absenteeism in daylight commercial office buildings, boost test scores in daylight classrooms [38], and accelerate recovery and shorten stays in daylight hospital patient rooms. Hourani and Hammad [39] reported impacts of daylight on students' health, emotions, attendance and performance. A 2 year study in U.S. elementary schools cleared more attendance by 3.6% for students in daylight classes than students in other classes depend mainly on electrical lighting and minimum day-lighting. Another study in U.S. schools investigated the impact of daylight on students' performance through scores' analysis for over (21,000) students. Whereas students in the most daylight classrooms showed progress 20% faster on math tests and 26% on reading tests within 1 year than students in classes depending on electrical lighting with minimum daylight [39].

3. Daylighting legislation

There are many types of building regulations, codes, standards or ordinances which are specifically related to ensure daylight in buildings. The requirements and regulations regarding daylight are very diverse. The existing daylighting standards in many European countries (comprehensive codes are for example in Germany [40] and Great Britain [41]) are more or less informative and are not intended to be applied in a prescriptive manner. The European Committee for Standardization will prepare the first European Code for daylighting in buildings and to define metrics for daylight and sunlight in all regularly occupied indoor spaces [42].

A good review of daylighting requirements of many sustainable rating systems was done in Ref. [43].

4. Selection of research studies

This paper systematically reviews recent research on the technologies or control systems of natural light in buildings. The main objective of such technologies or control systems is not only

to protect occupants from direct solar glare but also maximize daylight penetration into buildings based on occupants' preferences, whilst allowing for a reduction in electrical consumption for lighting and heating. The methodology used for this systematic review is described in [44,45], and consists of the following steps:

- Exhaustive search of the literature by applying pre-defined criteria for the identification of the most relevant articles in the field.
- Critical evaluation of the quality of the selected articles by synthesizing their content and summarizing the results and conclusions.

For this research, the data were obtained by searching databases of different disciplines (e.g. environmental and daylighting studies and public health). The search engines used were those on Internet, environmental and daylighting web pages. The key words for the searches were daylighting, sustainable building, healthy buildings and environmental impact of daylight and control systems of daylighting. The inclusion criteria for articles were explicitly defined in consonance with the characteristics of the study. To be included in the review, the article had to be an in-depth study of daylighting, its characteristics, influential factors, consequences, technologies or control systems, effects on human health and environment, etc.

The structure of this review reflects the inventory of possible control systems of daylighting in buildings. These control systems were identified by analyzing the contents of the articles. The articles analyzed in the review were retrieved from the following databases: Journal Citation Reports, Web of Knowledge, Web of Science, and Scopus. From each article, the research objectives, the description of the methodology applied or developed, the geographical location of the study, theoretical premises, computer tools used, and above all, the information in the conclusions regarding the technologies or control systems of daylighting in buildings were extracted.

5. Natural light controls and light guides in buildings

According to the International Energy Agency (IEA) [10], artificial lighting makes up 14% of electrical consumption in the European Union and 19% worldwide.

There is a great variety of systems to control and/or guide the natural light which penetrates the interior of a building, put in place with the aim of reducing energy consumption. These systems or strategies of control and/or guidance of natural light can be divided into two groups:

- Side-lighting systems
- Top-lighting systems.

The first group includes systems of lateral illumination where natural light enters the interior of a building through the sides. A window is the simplest example of this group of systems or strategies. Zain-Ahmed et al. [46] presented a study on energy savings achieved through the use of daylight in passive solar building design. They proved that by modifying the size of the windows, a minimum saving of 10% in electrical energy consumption is achieved.

In the second group, natural light enters the interior of a building from the top. A skylight would be the simplest example of this group.

The main objective of these systems and/or strategies of control and/or guidance of natural light is not only to maximize levels of natural light inside a building but also optimize the light quality in the environment for its occupants (an excess of natural light can be uncomfortable). The key to well-designed natural illumination lies in the control, not only of levels of light, but also in the direction and distribution of the light. In this way both the comfort of the occupants and the reduction in electrical energy consumption for lighting [47] and cooling [48] will be assured.

5.1. Side-lighting systems

Side-lighting systems are designed to avoid an unequal distribution of natural light which may occur through the use of traditional lateral windows. These systems achieve a more uniform, balanced distribution of natural light inside a building through the reduction of excessive levels of light near the windows and an increase in the light in areas situated far from the windows. In this article the side-lighting systems analyzed are

- Light shelves
- Prismatic glazing
- Mirrors and holograms
- Anidolic ceiling
- Louvres and blinds.

5.1.1. Light shelves

Light shelves are components placed horizontally in a window above eye level. As Ochoa and Capeluto [49] demonstrate, these systems protect the lower areas near a window from direct solar radiation. They also reduce the contrast between the light levels generated in the vicinity of the window and those at the back of the room. Edmonds and Greenup [50] showed that light shelves are a good device for shading and natural lighting.

Light shelves are divided into superior and inferior sections. Their job is to reflect the light which shines on them towards the surface of the ceiling in order to achieve a better penetration and more uniform distribution of light, whilst decreasing the electrical energy consumption for lighting. In this way Sanati and Utzinger [51] showed that spaces where the windows had been fitted with light shelves used less electricity for lighting than those with conventional windows.

As these systems operate by reflecting the light which falls upon them towards the surface of the ceiling, the geometry of both the ceiling and the light shelves plays a very important role in their performance. Freewan et al. [52], proved that the best ceiling is one which is curved in both the front and the rear of the room. In a subsequent study the authors analyzed the interaction between the different geometries of the light shelves when combined with a curved roof, finding the best light shelves are curved and bevelled [53]. Al-Sallal [54] revealed that a roof pitch of 5° contributes to a reduction in the difference in brightness between the ceiling and the back wall.

Light shelves affect the architectural and structural design of a building and must be considered at the beginning of the design phase as they require a specific roof type in order to function efficiently. Light shelves must be designed specifically for every window orientation, room configuration or latitude [55,56]. Although light shelves are only effective during the seasons of the year where light falls directly onto them, they help reduce glare. As they reduce levels of illumination they are not always apt for rooms with north exposure [49].

5.1.2. Prismatic glazing

Devices similar to prismatic glazing have been used for many years to adapt daylight in such a way so that the diffused solar

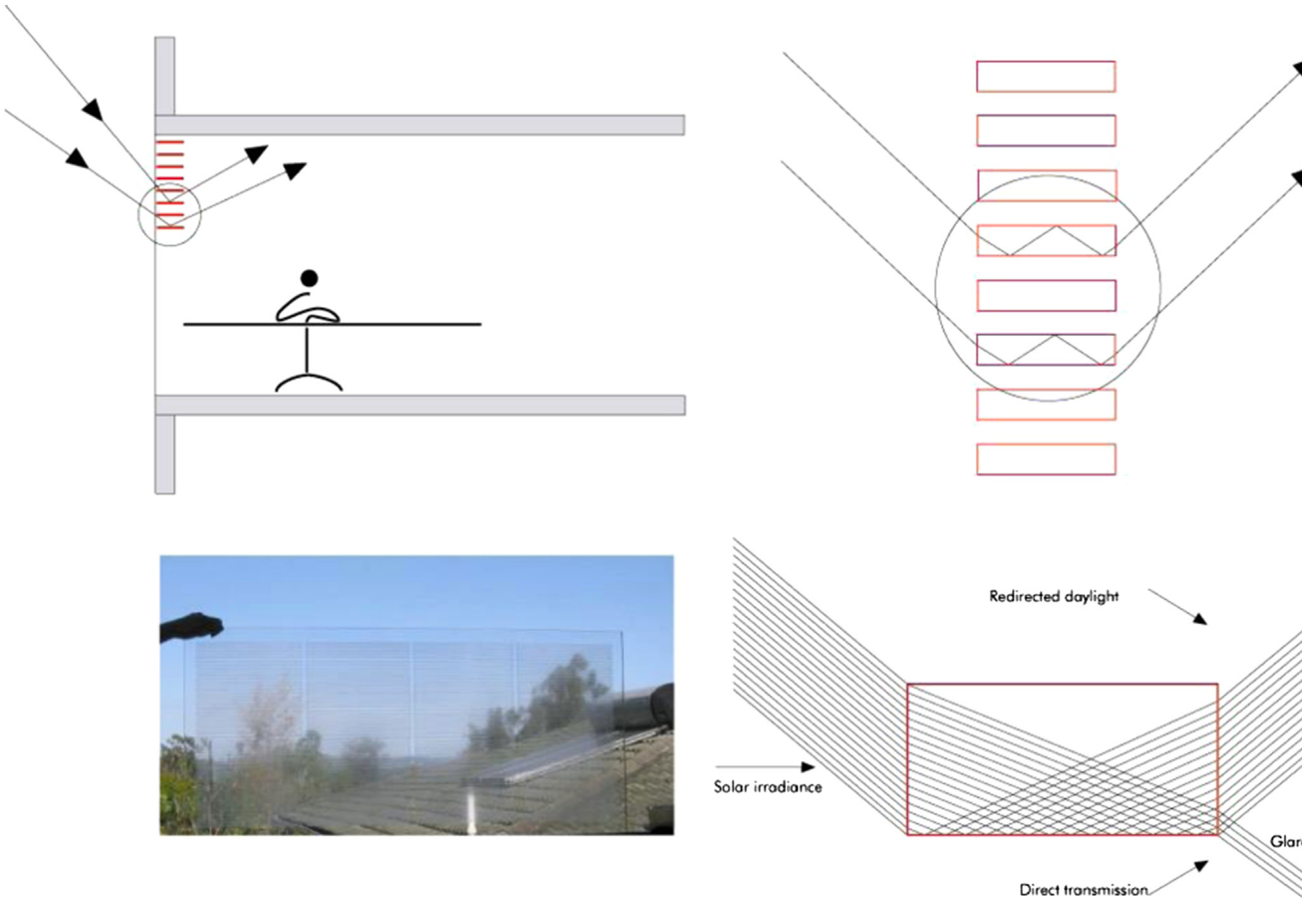

Fig. 1. Light deflection using prismatic glazing [21].

radiation enters into a building whilst the direct radiation is reflected [57]. Critten [58] showed that prismatic glass could be used to enhance winter sunlight in greenhouses, whilst Kurata [59] demonstrated the effects of a Fresnel prism in a greenhouse cover, concluding that the transmission of light in winter was increased whilst in summer it decreased.

Prismatic glazing follows the basic laws of reflection and refraction of sunlight to change the inbound direction of the light and redistribute it. Part of the incidental sunlight is reflected on the ceiling while the rest stays near the window (Fig. 1). In this way a better penetration and more uniform distribution of sunlight can be achieved [60]. Lorenz [61] proved that this heightened penetration and uniformity of light reduces electrical energy consumption for cooling as it offers a significant improvement in the thermal comfort of the users during the summer months. Along these lines, Christoffers [62] managed to reduce electrical energy consumption for cooling and heating by decreasing the direct solar radiation falling onto the front of a building by 10% in the summer whilst transmitting 90% of this radiation in winter.

Various studies have concentrated on different aspects of prismatic glazing, with the objective of improving the distribution of daylight inside rooms [63,64]. Some of the aspects which have been analyzed include design, thickness, deviation angle, amount of deviated light.

However, the effect of prismatic glazing when the sky is overcast is negligible. In this case the prismatic plates are placed between two transparent panes of glass at the top of the window. Along these lines Edmonds [65], analyzed a material of a similar thickness to conventional glass windows, with a prismatic glazed laminate placed between two panes. The resulting material offered a more efficient distribution of sunlight.

5.1.3. Mirrors and holograms

Mirrors and holographic sheets or Holographic Optical Elements (HOEs) allow a redirection of natural light, improving light penetration and distribution inside buildings [60]. Both systems offer large potential savings in energy and improved comfort for users [66]. Breitenbach and Rosenfeld [67] investigated the optical properties of holograms, concluding that, as they separate the majority of the light visible from the infrared part of the solar spectrum, they are an efficient means of both controlling natural light and optimizing sunlight gain.

Various authors have studied the environmental advantages of holograms. Müller [68] proved that through the use of holograms, electrical consumption for lighting could be reduced by more than 50% when complemented with an automatic control system for the lights. James and Bahaj [69] showed that the temperature in a greenhouse could be reduced by as much as 6.1 degrees if holograms were added to 62% of the glass.

However, according to Tholl et al. [70], holograms offer the disadvantage of reducing transparency in an environment whilst Klammt et al. [71] state that the high cost of holograms means that using them on a large scale is difficult. Furthermore Köster [21] concludes that mirror glass windows reduce the transmission of energy through the glazed surface. This means that, by reducing the external heat load resulting from solar irradiation into the building being reflected and/or absorbed in the outer skin, energy use for electric lighting is increased (Fig. 2).

5.1.4. Anidolic ceilings

The anidolic ceiling is a system which offers an improvement not only in the levels of natural light inside a building but also in

energy efficiency [72,73]. Wittkopf et al. [74] proved that more than 20% of electrical energy consumption for lighting could be saved using this system. For Courret et al. [75] this saving in electrical energy for lighting is 30%. Using a comparative study, these authors proved furthermore that personal appreciation of the luminous atmosphere is higher in a room with an anidolic ceiling, leading to a significant reduction in reading errors both on paper and on the screen. Scartezzini and Courret [76] showed that on an overcast day, the daylight factor, measured at the back of a room, increased by 1.7; this allows for a reduction in electrical energy consumption for lighting of a third. Furthermore, measurements of visual comfort recorded that, with an overcast sky, the anidolic ceiling offers better quality illumination than conventional glazing. Linhart and Scartezzini [77] proved that with anidolic lighting systems, lighting power densities can be reduced by at least 4 W/m^2 with no significant impact on visual comfort and efficiency; even a 3 W/m^2 reduction is a realistic possibility.

Fig. 2. Mirror facades darken the interior, making it necessary to switch on the lights during the day [21].

Vázquez-Moliní et al. [78], describe in detail the anidolic collecting system as a part of the comprehensive daylighting system. The day lighting system is based on a Truncated Compound Parabolic Concentrator (T-CPC) collection system that minimizes the system's dependence on solar incidence which means an appropriate behavior for virtually any time of year during working hours. Moreover the controlled aperture angle, limited by the collector array, reduces reflection losses.

Other authors such as Ochoa and Capeluto [49] proved that the anidolic ceiling offers high levels of illumination in quantitative terms. However, qualitatively, care must be taken over solar angles where the reflection hub may cause glare. Errors in the size or orientation of the hub may cause undesired reflections, even when the system's performance is good.

5.1.5. *Louvres and blinds*

Louvres and blinds are two systems designed to capture the sunlight entering into the front part of a room and redirect it towards the back. This increases light levels at the back of the room whilst reducing them at the front (Fig. 3).

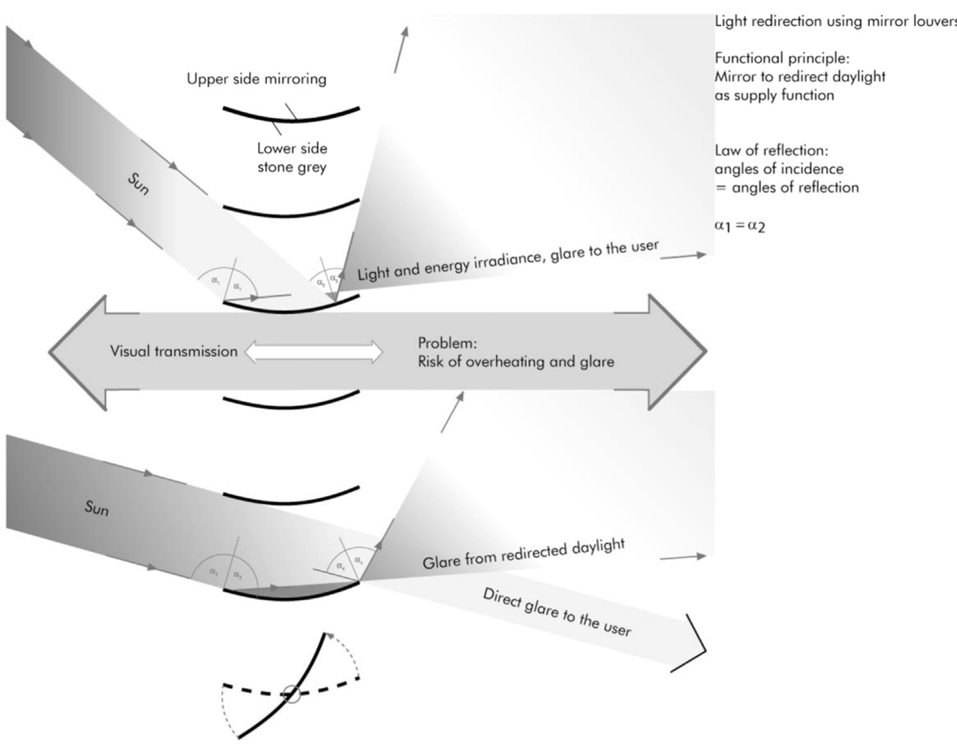

Fig. 3. Mirror blinds open [21].

Louvres and blinds are made up of numerous horizontal, vertical or sloping slats. Due to the discreet nature of the device, its optical (and thermal) properties are complex and depend on several parameters including louvre characteristics, tilt angle and solar angle of incidence. Rotation angle, shape, size, configuration and color of slats all have an impact on glare and visibility, but also on effective transmittance, absorption and reflectance of a window-blind system [79].

Much of the research carried out on louvres and blinds concentrates on calculating their optical properties and other questions relating to their control, employing experimental techniques [80–82], analytical models [83–85], semi-analytical and numerical methods [86–89] and ray-tracing simulation [90–92].

Numerous authors have studied the influence of louvres and blinds on electrical energy consumption in buildings. Along these lines, Hammad and Abu-Hijleh [93] examined the changes in electrical consumption in an office block situated in Abu Dhabi, in the United Arab Emirates. They compared this system with another, simpler method of using light dimmers controlled by a sensor. The results showed that the potential energy savings when using the dimmers was merely 24.4%, 24.45% and 25.19% in the south, east and west-facing facades, respectively. The proposed system of dynamic blinds together with the gradual light reduction strategy meant energy savings of 34.02%, 28.57% and 30.31% in a southern, eastern and western orientation, respectively. Saelens et al. [94] evaluated the influence on cooling demands and the peak cooling potential of a south-facing office when different models and perspectives were applied to simulate performance of external Louvre shading devices.

Oh et al. [95] optimized control strategies of slat-type blinds through two stages. In the first stage, double-sided blinds were suggested by applying different reflectance between the front and back of the slat and by fully rotating the slat when the system mode was switched between heating and cooling. When the double-sided blind was used alongside the controlled light dimmers, an energy saving of 24.6% could be achieved when compared to the baseline case, and simultaneously glare could be avoided. In the second stage, the control strategies of slat angle and up/down control logic were developed to fully remove glare and improve the energy efficiency. As a result, an energy saving of 29.2% could be achieved whilst glare was reduced to just 0.1%. Shen et al. [96], evaluated and compared the lighting, heating and cooling energy consumption, electric demand and visual comfort of different control strategies. The results showed that integrated controls achieve the lowest total energy in all cases. In most cases, Strategy 6 (Fully integrated lighting and daylighting control with blind tilt angle control without blind height control) achieves the lowest total energy. In mixed humid climates and buildings with interior blinds, Strategy 7 (Fully integrated lighting and daylight control with blind tilt angle and height control) achieves the lowest total energy.

Koo et al. [97], proposed a new method of blind control to maximize the comfort of the user and minimize energy consumption for heating on a clear day.

Palmero-Marrero and Oliveira [98] studied the effect of the louvre shading devices applied to different facades of a building at different latitudes. The results showed that the integration of louvre shading devices offered thermal comfort inside a building and could lead to significant energy savings, compared with a similar building without this type of shading devices.

Along these lines Leung et al. [99] showed that the reflective louvre system can increase working plane illuminance by up to 70% on a clear day. However this system did not generate reasonable savings in costs and presented the disadvantage of creating contrast. Dattalt [100] proved that external fixed horizontal louvres are effective not only in reducing the cooling loads in a building in the summer but also offer a reduction in the global yearly primary energy loads.

Athienitis and Tzempelikos [101] presented a methodology for a combined lighting–daylighting numerical simulation of an office space with an advanced window system incorporating motorized reflective blinds between the two panes. The energy savings using the methodology presented for the particular window system with integrated blinds may exceed 75% for overcast days and 90% for clear days, compared with the case of an office space with no daylighting/dimming control. Also, proper control of the blinds blocks direct solar radiation and reduces glare.

One disadvantage of louvres and blinds is that, if they are controlled manually by the occupants of a building, according to personal preferences, they often do not comply with the thermal, lighting and visual efficiency requirements [102–108]. The occupants may be out of the room when the blinds require adjustment. Furthermore, the occupants often close the louvres or blinds completely to avoid overheating and glare [95,109], reducing in this way the quantity of light. If this occurs, electrical energy consumption for both lighting and cooling will increase [110]. The occupants can also alter the position of the blinds to protect the space from direct sunlight, but they do not often readjust the position of the blinds in the absence of direct sunlight [90,101,102,111,112].

The solution to this problem lies in the use of automated blinds with an appropriate automated control system [102], which helps reach a balance between the right amount of natural light and maximum protection against overheating [94,95,97,105,113–115]. The advantages of automated blinds are as follows:

- They provide higher levels of natural light and better protection against overheating and glare inside a building [93].
- Better thermal efficiency and higher natural light penetration leading to savings in both cooling loads and lighting energy [93,95,106,116]. Galasiu et al. [117] presented the field-measured performance of two commercial photocontrolled lighting systems, continuous dimming and automatic on/off, as a function of various configurations of manual and photocontrolled automated venetian blinds. The results showed that under clear sky and without blinds both lighting control systems reduced the energy consumption for lighting on average by 50–60% when compared to lights fully on from 6 am to 6 pm. These savings, however, dropped by 5–45% for the dimming system, and by 5–80% for the automatic on/off system with the introduction of various static window blind configurations. The savings in lighting energy were more significant when the lighting control systems were used together with photocontrolled blinds. This was due to the capability of the blinds to adjust their position automatically in direct response to the variable daylight levels. Lee et al. [118], designed a dynamic venetian blind and dimmable electric lighting system to optimize daylight admission and solar heat gain rejection in real-time, while accommodating other occupants' considerations. The authors showed a significant energy saving (22–86%) and a reduction in peak demands (18–32%) using the automated venetian blind/lighting system instead of static venetian blinds with the same dimmable electric lighting system.
- They close automatically when the temperature inside a building or the levels of light become too high, and they reopen when the temperature and light decrease, to allow penetration of daylight [119].
- The control system adjusts automated blinds to block direct sunlight, avoiding in this way glare, and offering total daylight illumination and electrical illumination on the illumination level range of [102,104].

Table 1
Summary of research on natural light controls and guides systems.

System	Object/Methodology	Location	Building	Major findings/limitations	Ref.
Lightshelf/ anidolic	The system was simulated through Radiance in a prototype that responds to a deep office space typology for different seasons of the year and hours of the day. The system was compared for illuminance and glare performance.	Israel	Office	This system protects the lower areas near a window from direct solar radiation and it also reduces the contrast between the light levels generated in the vicinity of the window and those at the back of the room. The anidolic ceiling offers high levels of illumination in quantitative terms. However, qualitatively, care must be taken over solar angles where the reflection hub may cause glare. Errors in the size or orientation of the hub may cause undesired reflections, even when the system's performance is good.	[49]
Lightshelf	Traditional adaptations of tropical /sub tropical buildings to high ambient irradiance from high elevations are outlined. Some examples of optical systems designed to improve daylighting in tropical buildings are discussed.	Tropics	Office	The lightshelves are a good device for shading and natural lighting.	[50]
Lightshelf and blind	In the lightshelf zone, first the existing venetian blinds were relocated to the middle of the window height, and then the interior lightshelves were installed on the upper half of the windows. The measurement was performed under overcast sky condition with electric lights off and all venetian blinds retracted. To study the effect of the subdivided window on occupants' use of blinds and electric lighting, the data was gathered on blind positions and electric light usage.	Wisconsin	Office	The results suggest that in identical environmental conditions, occupants whose workstations were located within the lightshelf zone demonstrated a lower window occlusion than those who were located in the area with conventional windows. Additionally, occupants in the lightshelf zone used less electric lighting than those in regular window design area.	[51]
Lightshelf	The impact of ceiling geometries on the performance of lightshelves was investigated using physical model experiments and radiance simulations.	Sub-tropics	Office	The geometry of both the ceiling and the lightshelves plays a very important role in their performance. The best ceiling is one which is curved in both the front and the rear of the room and the best lightshelves are curved and bevelled.	[52,53]
Prismatic glazing	The reduction electrical energy consumption was investigated using a prismatic glazing unit consisting of two panes with interlocking, horizontal prismatic ribs with a triangular cross-section and a prism angle of 90°.	North or south latitudes between 30° and 60°	Office	This heightened penetration and uniformity of light reduces electrical energy consumption for cooling as it offers a significant improvement in the thermal comfort of the users during the summer months.	[61]
Prismatic glazing	This study estimates the technical potential for energy savings available from vertical daylighting strategies and explores additional savings that may be available if current dPOE research culminates in a successful market-ready product.	Chicago	Office	Results indicate that fully functional dPOE coatings, when paired with conventional vertical daylight strategies, have the potential to reduce energy use associated with U.S. commercial electric lighting demand by as much as 930 Tbtu. This reduction in electric lighting demand represents an approximately 85% increase in the energy savings estimated from implementing conventional vertical daylight strategies alone.	[64]
Hologram	The development and production of HOE's for controlling and directing the radiation of the sun which gives a broad scale of applications with high potential of energy saving and increase of comfort.	Dortmund (Germany), Southampton (UK) and Athens (Greece).	Office	A shading device with HOEs is a highly innovative system allowing "transparent shading". The view to the outside is nearly not affected, but the beam radiation is inhibit to penetrate the building. In combination with an automatic control system the energy consumption for cooling, heating and illumination in buildings can be reduced.	[66]
Hologram	This paper describes the potential application of solar control HOE applied as either a fixed plate or tracked solution. The single-element hologram focuses light, spectrally splits it and diverts unwanted infrared heat away from the solar cells.	UK	Greenhouse	The temperature in a greenhouse could be reduced by as much as 6.1 degrees if holograms were added to 62% of the glass.	[69]
Anidolic	The subject of this article is building energy saving on electrical lighting by anidolic integrated ceiling (AIC), compared in different daylight climates. The objective was to quantify the energy savings of AIC for a range of locations where such AIC has yet to be applied.	Singapore and Sheffield	Office	Computational simulations show that more than 20% of energy for electrical lighting can be saved. The energy savings are quite similar for both locations, with 21% for Singapore and 26% for Sheffield. Therefore, it is valid to conclude that AIC is a universal remedy to improve daylighting and energy efficiency in deep buildings.	[74]
Anidolic	The article gives a description of the anidolic systems, as well as an overview of their luminous performance, assessed experimentally within the framework of IEA Task 21.	Greece	Office	On an overcast day, the daylight factor, measured at the back of a room, increased by 1.7; this allows for a reduction in electrical energy consumption for lighting of a third. Furthermore, measurements of visual comfort recorded that, with an overcast sky, the Anidolic ceiling offers better quality illumination than conventional glazing.	[76]
Anidolic	All south-facing office rooms within the LESO solar experimental building in Lausanne (Switzerland) are equipped with a given type of ADS.	Lausanne (Switzerland)	Office	With Anidolic lighting systems, lighting power densities can be reduced by at least 4 W/m^2 with no significant impact on visual comfort and efficiency; even a 3 W/m^2 reduction is a realistic possibility.	[77]
Anidolic	The present paper describes in detail the anidolic collecting system as a part of the comprehensive daylighting system.	Madrid (Spain)	Non-residential buildings	The daylighting system minimizes on solar incidence which means an appropriate behavior for virtually any time of year during working hours. Moreover the controlled aperture angle reduces reflection losses.	[78]

Table 1 (*continued*)

System	Object/Methodology	Location	Building	Major findings/limitations	Ref.
Louvre	This research is aimed at exploring the influence of external dynamic louvres on the energy consumption.	Abu Dhabi-UAE.	Office	The results showed that the potential energy savings when using the dimmers was merely 24.4%, 24.45% and 25.19% in the south, east and west-facing facades, respectively. The proposed system of dynamic blinds together with the gradual light reduction strategy meant energy savings of 34.02%, 28.57% and 30.31% in a southern, eastern and western orientation, respectively.	[93]
Louvre	In this paper a ray-tracing method is developed to describe the global solar transmittance of louvre shading devices. The paper assesses the influence on the cooling demand and peak cooling power of a south oriented office cell when using different models and approaches to simulate the performance of exterior louvre shading devices.	Belgium	Office	Best results are achieved by implementing solar radiation weighted monthly averages allowing to estimate the cooling demand and peak cooling power within 3%.	[94]
Louvre/ blind	The optimized automatic control strategies of slattype blinds were developed to efficiently adjust the solar radiation through the window, which can improve both energy efficiency and visual comfort by taking into account cooling, heating and lighting energies as well as the glare phenomena.	Daejeon City, South Korea	Office	When the double-sided blind was used alongside the controlled light dimmers, an energy saving of 24.6% could be achieved when compared to the baseline case, and simultaneously glare could be avoided. In the second stage, the control strategies of slat angle and up/down control logic were developed to fully remove glare and improve the energy efficiency. As a result, an energy saving of 29.2% could be achieved whilst glare was reduced to just 0.1%.	[95]
Louvre	The effect of the louvre shading devices applied to different facades of a building at different latitudes was studied.	Mexico (Mexico), Cairo (Egypt), Lisbon (Portugal), Madrid (Spain) and London (UK)	Office	The results showed that the integration of louvre shading devices offered thermal comfort inside a building and could lead to significant energy savings, compared with a similar building without this type of shading devices.	[98]
Louvre	This study examines the effectiveness of installing a controlled semi-silvered reflective louvre system in the clerestory portion of a direct solar (north) facing facade system in a deep cellular office space.	Melbourne, Australia	Office	The reflective louvre system can increase working plane illuminance by up to 70% on a clear day. However this system did not generate reasonable savings in costs and presented the disadvantage of creating contrast.	[99]
Louvre/ blind	Methodology for a combined lighting–daylighting numerical simulation of an office space with an advanced window system incorporating motorized reflective blinds between the two panes.	Montreal	Office	The energy savings using the methodology presented for the particular window system with integrated blinds may exceed 75% for overcast days and 90% for clear days, compared with the case of an office space with no daylighting/dimming control. Also, proper control of the blinds blocks direct solar radiation and reduces glare.	[101]
Blind	This study aims to find out whether the environmental performance of a building can be improved by the application of an automated Venetian blind in comparison to a manual or motorized Venetian blind and whether occupants may feel discomfort by the application of an automated Venetian blind in the summer season.	Seoul, Korea	Office	The potential energy savings and the comfort enhancement when using the automated blind was confirmed.	[120]
Skylight	The main aim of this article is to determine a suitable shape for lightscoop skylights, whose main characteristic is a vertical opening oriented in the opposite direction to the solar trajectory, in order to ensure maximum illuminance on the work plane within a room.	–	Museum or library	The curved shape produces an increase of average daylight factors close to 3.5% compared with the rectangular shape, while the sawtooth shape produces a decrease of average daylight factors close to 3.5% in a room under overcast sky conditions.	[127]
Skylight	This study reviews a concept to understand the passive behavior of solar radiation in the form of light and heat that falls on, interacts with, and is emitted from a skylight system in a single-story building. The study method is theoretically based on descriptive analysis to assess design requirements.	Malaysia	Single-story building	Skylight systems are inappropriate for direct application in the tropics to balance the thermal and lighting loads. Therefore, these systems should be integrated by using shading, glare protection, proper use of reflective surfaces, reflectors, prisms and multi-pane, using splaying and wells for skylight, as well as double-layered roof system, and taking advantage of different geometries, roof angles, orientations, and complicated roof profiles.	[128]
Skylight	A model to estimate daylight factor was investigated and validated using experimental hourly inside and outside illuminance data of an existing skylight integrated vault roof mud-house in composite climate of New Delhi.	New Delhi (India)	House	Through the study and validation of a model used to estimate daylight factors, showed a potential yearly saving in electrical energy for lighting of 973 kWh/year. This saving is equivalent to 1526 kg/year of CO_2 emissions.	[131]
Sawtooth	The experimental results and the specific analysis of thermal energy savings carried out to analyze energy efficiency in a building with a sawtooth system installed.	Almeria (Spain)	University	Simulations have shown that, the needed annual thermal loads required to obtain comfort conditions are lower into MEDUCA (Model Educational Buildings for Integrated Energy Efficient Design, contract BU 1006/96) courtyard than in a conventional sawtooth roof. The loads values are different depending on monthly requirements.	[132]

Light pipe	In this research, a remote source lighting system (RSL) is introduced to illuminate the enclosed lift lobbies. The system composed of prismatic light pipe and optic fiber to address the problem of limited headroom.	Hong Kong	Highrise commercial and residential	This lighting system can solve the energy consumption problem in the lift lobby in terms of renewable energy use and natural lighting application. The prismatic light pipe can work in both clear and overcast sky conditions. However, there are limiting factors that affect the performance of it such as orientation, solar azimuth angle and angle of incident light.	[136]
Light pipe	The aim of this study is to illuminate a windowless room via a light-pipe and dimmable electronic ballasts.	Istanbul (Kadikoy)	Office	Approximately 30% saving was achieved by the proposed controller implementation. In summer, the energy saving from the lighting system will be even higher.	[137]

Ji-Hyun et al. [120], set out to decide whether the environmental performance of a building could be improved through the use of an automated venetian blind when compared with a manual or motorized blind and whether the occupants would feel discomfort when using an automated blind during the summer months. In terms of energy consumption for cooling, automated blinds reduced this consumption compared to fully-opened manual blinds as the automated blinds blocked solar radiation according to the outdoor weather conditions while consuming more energy compared to manual blinds which is fully closed. However, if the additional energy consumption for lighting needed due to the interception and blocking of sunlight is considered, the overall environmental performance of the automated blinds is nearly equal to that of manual blinds when fully opened. As the room illuminance level continuously exceeded the upper limit of 3340 lx, it would be reasonable to assume that the blinds ought to have been fully closed and artificial lighting used. Furthermore, if the additional energy consumption for lighting is considered, the overall environmental performance of the automated blinds is better than that of manual blinds when fully closed. As for the comfort of the occupants, in the case of the automated blinds, the slat angle is controlled to cut off direct sunlight, which reduces the discomfort from excessive solar radiation and direct sunlight. In addition, daylight can be introduced to provide a feeling of openness.

5.2. Top-lighting systems

Typical top-lighting systems are

- Skylight
- Roof monitor
- Sawtooth
- Light pipe.

Garcia-Hansen et al. [121], outline the possible energy savings and greater efficiency obtained through the use of top-lighting systems (skylights, roof monitors and clerestory roof windows) in cold areas of the typically template climate of Argentina. The results indicate that heating, ventilation and lighting costs can be significantly reduced through the implementation of these passive solar systems.

5.2.1. Skylight systems

A skylight system consists of a horizontal or sloping opening in the roof of a building. It is designed to capture sunlight when the sun is at its zenith, allowing daylight to penetrate into buildings. This system of natural illumination can only be used on the top floor of a multi-storey building or in single-storey buildings [122].

To quantify the efficiency of these skylights, some studies employ scale models [123] or computer simulators [124,125]. In this way, Henriques et al. [126] developed a skylight system which responded to the environmental demands of a building's exterior as well as its interior. Parametric and environmental software analysis was used to generate and assess solutions. Acosta et al. [127] conducted an analysis in order to determine the most suitable set up for a skylight system, in order to ensure maximum working plane illuminance within a room. Treado et al. [48] concluded that skylights are the most efficient option for minimizing total energy use in a building for heating, cooling and lighting. They are furthermore the most effective source of natural lighting, achieving a reduction of 77% in electrical energy consumption. Although, for Al-Obaidi et al. [128] the use of this system is limited to specific climatic regions because of its considerable effect on the indoor environment.

Other researchers have based their studies on the classic treatises dealing with daylight [129]. In this way Tsangrassoulis and Santamouris [130] offer a practical methodology to estimate the efficiency of this system and determine the quantity of light reaching the interior of a building where these devices have been installed. This methodology is based on the flux transfer approach, used to model the distribution of light energy in round skylights of different proportions of height and width, wall reflectance and transmittance of the glass. Chel et al. [131] through the study and validation of a model used to estimate daylight factors, showed a potential yearly saving in electrical energy for lighting of 973 kWh/year. This saving is equivalent to 1526 kg/year of CO_2 emissions.

5.2.2. *Roof monitor and sawtooth systems*

Roof monitors and sawtooth are lighting systems which differ mainly in form. They consist of vertical or sloping openings in the roof used to capture light. These openings can be designed to reflect sunlight at certain moments of the day or the year, depending on the requirements of a building. The roof monitor system allows sunlight to penetrate a room in winter when the sun is low in the sky, but not during the summer months.

Heras et al. [132] present the experimental results and the specific analysis of thermal energy savings carried out to analyze energy efficiency in a building with a sawtooth system installed.

5.2.3. *Light pipe systems*

The light pipe system consists of a dome skylight (to capture sunlight), a reflective tube (to reflect the sunlight to interior spaces) and a diffuser assembly (placed inside the room to be lit). The dome must be ultraviolet and impact resistant, to protect the tube from dust and rain. Commonly two types of light pipe system are used straight and elbow bends [133].

The light pipe system is an energy-saving technology offering the possibility of illuminating even the farthest depths of an interior space. Darula et al. feel that straight light tubes offer a unique opportunity for carrying natural light to the farthest corners of a room even in spaces with no windows. [134]. However, for Kocifaj et al. [135] the light tube must be pointing directly at the sun to reach its full efficiency potential. Wong and Yang [136] demonstrated that light pipe system can work in both clear and overcast sky conditions. However, there are limiting factors that affect the performance of it such as orientation, solar azimuth angle and angle of incident light.

Görgülü and Ekren [137] lighted a windowless room with a light tube and dimmable electronic ballasts. A saving of around 30% was made using the proposed controller. In the summer months, the energy saved on illumination would be greater.

Jenkins and Muneer [138–140] discussed numerous design models/methods to use in predicting light levels in light tubes, in other words, a tool to quantify the best configuration for light tubes in any given situation. A year later, Jenkins et al. [141] developed a model which employed the cosine law of illumination to trace the distribution of the light diffusing light tube, taking into consideration pipe elbow pieces or bends.

Canziani et al. [16] proved that the light pipe system offers an energy saving potential for both electrical energy (used in artificial illumination) and thermal (heating and cooling) energy. They are furthermore capable of avoiding unwanted phenomenon such as direct irradiation, glare, and overheating. They uniformly distribute sunlight to assure adequate luminous comfort.

Table 1 presents a summary of research on natural light controls and guides systems.

Table 2
Comparison between the different systems of control and guidance of natural light.

Category	System	Climate	Location	Criteria for the choice the elements				
				Glare protection	**View outside**	**Light guiding into depth of room**	**Homogeneous illumination**	**Saving of energy**
Side-lighting systems	Light shelves	All climates	Vertical windows	Depends	Yes	Yes	Yes	Yes
	Prismatic glazing	All climates	Vertical windows, skilights	Depends	No	Depends	Depends	Yes
	Mirrors and holograms	Temperate climates/All climates	Skilight, glazed and roofs	Depends	No	No	Yes	Depends
	Anidolic ceiling	Temperate climates	Skylight	Depends	No	No	Yes	Yes
	Louvres and Blinds	All climates	Vertical windows	Yes	Depends	Yes	Yes	Yes
Top-lighting systems	Skylight	Hot climates, sunny skies	Skylights	Depends	No	Yes	Yes	Yes
	Roof monitor	All climates	Roofs	Depends	No	No	Depends	Yes
	Sawtooth	All climates	Roofs	Depends	No	No	Depends	Yes
	Light pipe	All climates, sunny skies	Skylights	Yes	No	Yes	Yes	Yes

6. Conclusions

6.1. Major survey findings

Traditional strategies of sun protection reduce the energy transmission through glazed building components using darkened solar shadings and/or mirror glass. The aim here is to reduce the external heat load resulting from solar irradiation into the building being reflected and/or absorbed in the outer skin. This fails to provide the buildings with sufficient natural daylight. The result is an increased use of energy for electric lighting, so that in terms of total energy consumption in these buildings, the mirror glazing often results in a negative energy balance.

Through a well-designed, controlled use of natural light, employing technologies or systems which ensure the penetration of light throughout the whole building, energy consumption designated to lighting and air conditioning can be kept at a minimum.

In accordance with the research analyzed, all of the systems and/or strategies of control and/or guidance of natural light guarantee the penetration of natural light into the building, thus reducing the electrical energy consumption for lighting and cooling. They simultaneously improve the thermal and visual comfort of the users of a building. However numerous studies have also brought to light various disadvantages presented by these systems:

- Skylight systems are inappropriate for direct application in the tropics to balance the thermal and lighting loads. Therefore, these systems should be integrated by using shading, glare protection, proper use of reflective surfaces, reflectors, prisms and multi-pane, using splaying and wells for skylight, as well as double-layered roof system, and taking advantage of different geometries, roof angles, orientations, and complicated roof profiles.
- Light shelves affect the architectural and structural design of a building and must be considered at the start of the design phase as they require a relatively high roof in order to function efficiently. These systems must be specifically designed to fit every window orientation, room configuration and latitude. The performance of light shelves is reduced with Eastern or western orientations and in climates where the conditions are predominantly overcast.
- Prismatic glazing has a negligible effect when the sky is overcast. In such conditions the prismatic plates are placed between two transparent panes of glass at the top of the window.
- The disadvantages of using holograms are twofold. Firstly, holograms reduce transparency in an environment and secondly their excessive cost means that they cannot often be used on a large scale. The disadvantage of mirror glass windows is that they reduce the transmission of energy through the glazed surface. This means that, by reducing the external heat load resulting from solar irradiation into the building being reflected and/or absorbed in the outer skin, energy use for electric lighting is increased.
- The Anidolic ceiling offers high levels of illumination in quantitative terms. However, qualitatively, care must be taken over solar angles where the reflection hub may cause glare. Errors in the size or orientation of the hub may cause undesired reflections, even when the system's performance is good.
- One disadvantage of louvres and blinds is that, if they are controlled manually by the occupants of a building, according to personal preferences, they often do not comply with the thermal, lighting and visual efficiency requirements. The solution to this problem is automated blinds. These are fitted with an appropriate automated control which helps achieve a balance between the correct amount of natural light and maximum protection from overheating.
- The light pipe system is an energy-saving technology offering the possibility of illuminating even the farthest depths of an interior space. However, the light tube must be pointing directly at the sun to reach its full efficiency potential. Prismatic light pipe can work in both clear and overcast sky conditions. However, there are limiting factors that affect the performance of it such as orientation, solar azimuth angle and angle of incident light.

Table 2 provides a comparison between the different systems of control and guidance of natural light.

6.2. Future perspectives

- The correct manipulation and exploitation of the sun and daylight is vital as an energy-saving resource and must be treated as a key element in the development of energy concepts.
- Occupants' attitudes and preferences pose significant impact on the usage of the proposed control systems and consequently, the optimization of building design and comfort management is yet an open challenge.
- An important trend of the future research must constitute quantification of the energy savings (lighting, heating and cooling) and evaluation of the impact on the occupants' satisfaction.
- Various simulation techniques that allowing the modeling of buildings with these systems of control and guide need to be future research objectives.

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